Title
Overview of the Lifecycle Emissions Model (LEM)

Author
Delucchi, Mark A.

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OVERVIEW OF THE LIFECYCLE EMISSIONS MODEL (LEM)

Mark A. Delucchi

Institute of Transportation Studies
University of California
One Shields Avenue
Davis, California 95616

madelucchi@ucdavis.edu

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Introduction

The task of developing and evaluating strategies to reduce emissions of urban air pollutants and greenhouse gases is complicated. There are many ways to produce and use energy, many sources of emissions in an energy lifecycle, and several kinds of pollutants (or greenhouse gases) emitted at each source. An evaluation of strategies to reduce emissions of greenhouse gases must be broad, detailed, and systematic. It must encompass the full "lifecycle" of a particular technology or policy, and include all of the relevant pollutants and their effects. Towards this end, I have developed a detailed, comprehensive model of lifecycle emissions of urban air pollutants and greenhouse gases from the use of variety of transportation modes.

The Lifecycle Emissions Model (LEM) estimates energy use, criteria pollutant emissions, and CO2-equivalent greenhouse-gas emissions from a variety of transportation and energy lifecycles. It includes a wide range of modes of passenger and freight transport, electricity generation, heating and cooking, and more. For transport modes, it represents the lifecycle of fuels, vehicles, materials, and infrastructure. It energy use and all regulated air pollutants plus so-called greenhouse gases. It includes input data for up to 20 countries, for the years 1970 to 2050, and is fully specified for the U. S. The remainder of this section provides a further overview of the LEM.

Transportation modes in the LEM

The LEM calculates lifecycle emissions for the following passenger transportation modes:

- light-duty passenger cars (internal-combustion engine vehicles [ICEVs] operating on a range of fuel types [see below]; battery-powered electric vehicles [BPEVs]; and fuel-cell electric vehicles, with or without an auxiliary peak-power unit [FCVs];

- full-size buses (ICEVs and FCVs)
- mini-buses (albeit modeled crudely)
- mini-cars (ICEVs and BPEVs)
- motor scooters (ICEVs and BPEVs)
- bicycles
- heavy-rail transit (e.g., subways)
- light-rail transit (e.g., trolleys)

and the following freight transport modes:

- medium and heavy-duty trucks
- diesel trains
- tankers, cargo ships, and barges
- pipelines

Fuel and feedstock combinations for motor vehicles

For motor vehicles, the LEM calculates lifecycle emissions for a variety of combinations of end-use fuel (e.g., methanol), fuel feedstocks (e.g., coal), and vehicle types (e.g., fuel-cell vehicle). For light-duty vehicles, the fuel and feedstock combinations included in the LEM are:

Fuel --> ↓ Feedstock	*Gasoline*	*Diesel*	*Methanol*	*Ethanol*	*Methane (CNG, LNG)*	*Propane (LPG)*	*Hydrogen*	*Electric*
Petroleum	**ICEV, FCV**	**ICEV**				**ICEV**		**BPEV**
Coal	**ICEV**	**ICEV**	**ICEV, FCV**					**BPEV**
Natural gas		**ICEV**	**ICEV, FCV**		**ICEV**	**ICEV**	**ICEV, FCV**	**BPEV**
Wood or grass			**ICEV, FCV**	**ICEV, FCV**	**ICEV**			**BPEV**
Soybeans		**ICEV**						
Corn				**ICEV**				
Solar power							**ICEV, FCV**	**BPEV**
Nuclear power							**ICEV, FCV**	**BPEV**

The LEM has similar but fewer combinations for heavy-duty vehicles HDVs, mini-cars, and motor scooters.

Fuel, material, vehicle, and infrastructure lifecycles in the LEM

The LEM estimates the use of energy, and emissions of greenhouse gases and urban air pollutants, for the complete lifecycle of fuels, materials, vehicles, and infrastructure for the transportation modes listed above. These lifecycles are constructed as follows:

Lifecycle of fuels and electricity:

- **end use**: the use of a finished fuel product, such as gasoline, electricity, or heating oil, by consumers;
- **dispensing of fuels**: pumping of liquid fuels, and compression or liquefaction of gaseous transportation fuels
- **fuel distribution and storage**: the transport of a finished fuel product to end users; for example, the shipment of gasoline by truck to a service station. Includes operation of bulk-service facilities;
- **fuel production**: the transformation of a primary resource, such as crude oil or coal, to a finished fuel product or energy carrier, such as gasoline or electricity. Includes a detailed model of emissions and energy use at petroleum refineries;

- **feedstock transport**: the transport of a primary resource to a fuel production facility; for example, the transport of crude oil from the wellhead to a petroleum refinery. Includes a complete country-by-country accounting of imports of crude oil and petroleum products by country;

- **feedstock production**: the production of a primary resource, such as crude oil, coal, or biomass. Based on primary survey data at energy-mining and recovery operations, or survey or estimated data for agricultural operations.

Lifecycle of materials:

- crude-ore **recovery** and finished-material **manufacture**: the recovery and transport of crude ores used to make finished materials, and the manufacture of finished materials from raw materials (includes separate characterization of non-energy-related process-area emissions);

- the **transport** of finished materials to end users.

Lifecycle of vehicles:

- **materials use**: see the "lifecycle of materials";

- **vehicle assembly**: assembly and transport of vehicles, trains, etc.;

- **operation and maintenance**: energy use and emissions associated with motor-vehicle service stations and parts shops, transit stations, and so on;

- **secondary fuelcycle** for transport modes: building, servicing, and providing administrative support for transport and distribution modes such as large crude-carrying tankers or unit coal trains.

Lifecycle of infrastructure:

- **energy use and materials production**: the manufacture and transport of raw and finished materials used in the construction of highways, railways, and so on; energy use and emissions associated with the actual construction of the transportation infrastructure. (Presently these are represented crudely; future versions of the LEM will have a more detailed treatment of the infrastructure lifecycle.)

Sources of emissions in lifecycles

The LEM characterizes greenhouse gases and criteria pollutants from a variety of emission sources:

- from the combustion of fuels that provide process energy (for example, the burning of bunker fuel in the boiler of a super-tanker, or the combustion of refinery gas in a petroleum refinery);
- as a result of the evaporation or leakage of energy feedstocks and finished fuels (for example, from the evaporation of hydrocarbons from gasoline storage terminals);
- from the venting, leaking, or flaring of gas mixtures that contain greenhouse gases (for example, the venting of coalbed gas from coal mines);
- as a result of chemical transformations that are not associated with burning process fuels (for example, the curing of cement, which produces CO_2, or the denitrification of nitrogenous fertilizers, which produces N_2O, or the scrubbing of sulfur oxides (SO_x) from the flue gas of coal-fired power plants, which can produce CO_2);
- as a result of changes in the carbon content of soils or biomass, or emissions of non-CO_2 greenhouse from soils, due to changes in land use.

Pollutant tracked in the LEM

The LEM estimates emissions of the following pollutants:

- carbon dioxide (CO_2);
- methane (CH_4);
- nitrous oxide (N_2O);
- carbon monoxide (CO);
- nitrogen oxides (NO_x);
- nonmethane organic compounds (NMOCs), weighted by their ozone-forming potential;
- sulfur dioxide (SO_2J);
- total particulate matter
- particulate matter less than 10 microns diameter (PM_{10});
- chlorofluorocarbons (CFC-12);
- hydrofluorocarbons (HFC-134a);
- the CO_2-equivalent of all of the pollutants above

Ozone (O_3) is not included in this list because it is not emitted directly from any source in a fuelcycle, but rather is formed as a result of a complex series of chemical reactions involving CO, NO_x, and NMOCs.

The LEM estimates emissions of each pollutant individually, and also converts all of the pollutant into CO_2-equivalent greenhouse-gas emissions. To calculate total CO_2-equivalent emissions, the model uses CO_2-equivalency factors (CEFs) that convert mass emissions of all of the non-CO_2 gases into the mass amount of CO_2 with an equivalent effect on global climate. These CEFs are similar to but not necessarily the same as the "Global Warming Potentials" (GWPs) used by the Intergovernmental Panel on Climate Change (IPCC). The CEFs are discussed in a separate section of the model documentation.

Material commodities in the LEM

Finally, the LEM includes the following materials:

- plain carbon steel
- high strength steel
- stainless steel
- recycled steel
- iron
- advanced composites
- other plastics
- fluids and lubricants
- rubber
- virgin aluminum
- recycled aluminum
- glass
- copper
- zinc die castings
- powdered metal components
- other materials (lead)
- sodium
- sulfur
- titanium
- sulfuric acid
- potassium hydroxide
- nickel and compounds
- lithium
- cement
- concrete
- limestone

Note that recycled steel and recycled aluminum are treated as separate materials from virgin steel and virgin aluminum. In this way, the full lifecycle of materials including recyling is explicitly represented.

Input: projections of energy use and emissions

As part of a major revision to the LEM, I have added projections of energy use and emissions, or changes in energy use and emissions, for the period 1970 to 2050. The user now specifies any target year between 1970 and 2050, and the model looks up or calculates energy-use intensities, emission factors, or other data for the specified year.

There are several different kinds of projections in the LEM: look-up tables (usually based on energy-use or emissions projections from the EIA), constant percentage changes per year, logistic functions with upper *or* lower limits, and logistic functions with upper *and* lower limits. These projections are discussed in more detail in a separate section of the model documentation.

Major outputs of the LEM

The LEM produces the following tables of results (discussed in more detail in a separate section of the model documentation):

- emissions per mile from motor vehicles: CO_2-equivalent emissions (in g/mi) by stage of fuelcycle and for vehicle manufacture, for the feedstock/fuel/vehicle combinations shown above;

- emissions from electricity use: CO_2-equivalent emissions (in g/kWh-delivered) for different sources of electricity generation;

- emissions from use of heating fuels: CO_2-equivalent emissions (in g/10^6-BTU-heat-delivered) for natural gas, LPG, electricity, and fuel oil;

- summary of % change in lifecycle g/mi emissions from alternative-fuel vehicles, relative to conventional gasoline LDVs or diesel HDVs;

- BTUs of process and end-use energy per mile of travel by stage of lifecycle, for different feedstock/fuel/vehicle combinations;

- breakdown of energy use by type of energy (e.g., diesel fuel, natural gas, propane), stage of lifecycle, and feedstock/fuel combination;

- vehicle characteristics: input data and results regarding vehicle weight and energy use;

- emissions from EVs, by region: a macro runs the model for regional data for EV recharging and prints the g/mi results for up to six different regions;

- emissions by IPCC sector: The g/mi results for vehicles are mapped into the IPCC sectors used in GHG accounting (e.g., “energy/road transport,” “energy/industry,” “land-use/forestry”);

• emissions by geographic sector: The g/mi results for vehicles are mapped into a geographic framework that distinguishes in-country from outside-of-country emissions;

• emissions by individual pollutant: one set of tables reports emissions of each individual pollutant (not weighted by CO_2-equivalency factors) for each stage of the upstream fuelcycle for each feedstock/fuel; another table does the same for vehicle manufacture and assembly;

• CO_2-equivalent emissions by pollutant: a new table summarizes the contribution of each pollutant to upstream fuelcycle CO_2-equivalent emissions;

• emissions from complete transportation scenarios: a new table of results shows g/passenger-mi emissions from a user-specified mix of travel by conventional motor vehicles, alternative-fuel vehicles (including electric vehicles), mini-cars, scooters, buses, trolleys, subways, bicycles, and walking;

• print macros: the LEM has macros that run the model for up to 40 different target years and then prints a pre-selected group of results tables in publication-ready format;

• emissions from other countries: the LEM can be programmed to calculate all results for the characteristics of any of up to 20 different countries. Separate data files exist within the LEM for each of the countries.

Overview of revisions to the LEM (since 1993 version)

The structure and input data of the LEM have been completely overhauled. For example, the inputs and model structure for vehicle emissions, vehicle fuel economy, feedstock recovery, transportation of feedstocks, fuel production, and distribution of fuels have been redone to be more detailed, flexible, consistent, and realistic. Many data on energy use, fuel characteristics, and emissions are estimated or projected from 1970 to 2050.

The output has been cleaned up and presented in considerably more detail. Estimates of g/10^6 BTU emissions are presented for each GHG (without the CEF weighting), for each stage of all of the fuelcycles. Fuelcycle GHG emissions for electric vehicles are calculated for the U.S. and each of six regions. A macro runs the LEM for up any target year and prints all of the main results in publication-ready tables.

Many major new components have been added, most notably:

• projections of energy use, emissions, emission control, and other parameters through the year 2050

• updated energy use parameters and emission factors, on the basis of EPA's standard emission-factor handbook, AP-42, the IPCC's *Revised 1996 IPCC Guidelines for National GHG Emission Inventories,* and other sources

• models and default data to represent emissions for other countries (e.g., Canada) (Appendix B)

• detailed original calculations of CO_2-equivalency factors for all gases, including a complete (albeit preliminary) representation of the nitrogen cycle

• several modes added: mini-cars, motor scooters, mini buses, heavy-rail transit, light-rail transit, and bicycling

• PM and SO_2 added as greenhouse gases and urban air pollutants;

• NMOCs weighted by their ozone-forming potential

• a mobile-source emission factor model, akin to a highly simplified version of the EPA's MOBILE model

• update and revision of the representation and data for the modeling of the lifecycle of materials (Appendix H)

• more detailed treatment of motor-vehicle energy use, on the basis of weight, thermal efficiency, and aerodynamic drag

• new estimation of the relationship between vehicle weight, materials composition, and fuel economy

• fuel economy estimated as a function of number (weight) of passengers in cars, buses, mini-buses, mini-cars, and scooters

• fuel economy and hence GHG emissions estimated as a function of vehicle payload, including number of passengers in cars or buses

• light-duty fuel cell vehicles using gasoline, methanol, ethanol, or hydrogen, with or without an auxiliary peak-power unit

• a new model of refinery emissions, based on emissions from individual process areas

• a more detailed calculation of emissions from the use of oxygenates

• a much more detailed treatment emissions from corn/ethanol and wood bio-fuel cycles

• perennial grasses as a feedstock for the production of ethanol

• soybeans to biodiesel fuelcycle (Appendix A)

• natural gas to diesel fuel via the Fischer-Tropsch (F-T) process

• F-T diesel of methanol made from associated natural gas that otherwise would be vented or flared

• natural gas to hydrogen via reforming

• coal to synthetic crude oil

• diesel fuel in LDVs, and gasoline in HDVs

• lifecycle emissions from the use of forklifts

• lifecycle emissions from the use of motor scooters

• an option to specify HDVs as buses rather than trucks

• a distinction between large-scale centralized liquefaction and small-scale liquefaction at service stations, for LNG and LH_2

• a detailed analysis of energy used to manufacture agricultural chemicals

• a model of changes in carbon sequestration in biomass and soil due to changes in land use (including changes associated with fossil-fuel production)

• more detailed representation of emissions of nitrogen species from soils, due to cultivation, and fertilizer use (Appendix C)

• representation of feedstock production and fuel production in physical input/output terms

• detailed tracking of imports of crude oil, and venting and flaring emissions and refining emissions in individual exporting countries or regions

• tracking of imports and coal, and venting of coalbed methane in individual exporting countries or regions

• tracking of source of enrichment of uranium, with different energy intensities for different enriching countries

• a detailed representation of natural gas transmission and distribution

• added explicit representation of international transport of coal

• a more consistent and detailed representation of feedstock and fuel transport

• emissions from energy use by service stations and marketing facilities

• fuelcycle emissions from the use of NG, LPG, fuel oil, and electricity for space heating and water heating

• rudimentary treatment of the extent to which alternative-fuel production displaces existing production or stimulates new demand

• a new treatment of "own use" of fuel

• explicit representation of geographic sources and shipping of materials and motor vehicles

Overall, the present model is more powerful, and quite a bit easier to use, than the previous model. In general, the the overall affect of the revisions is to make alternative fuels more attractive.

Documentation of the model

The 1997 version of the model is documented in several reports, shown below. Complete up-to-date working documentation is available from the author.

M. A. DeLuchi, *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*, ANL/ESD/TM-22, Volume 1, Center for Transportation Research, Argonne National Laboratory, Argonne, Illinois, November (1991). 142 pp.

M. A. DeLuchi, *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*, ANL/ESD/TM-22, Volume 2, Appendices A-S, Center for Transportation Research, Argonne National Laboratory, Argonne, Illinois, November (1993). 524 pp.

M. A. Delucchi, *Emissions of Criteria Pollutants, Toxic Air Pollutants, and Greenhouse Gases, from the Use of Alternative Transportation Modes and Fuels,* UCD-ITS-RR-96-12, Institute of Transportation Studies, University of California, Davis, January (1996). 150 pp.

M. A. Delucchi and T. E. Lipman, *Emissions of Non-*CO_2 *Greenhouse Gases from the Production and Use of Transportation Fuels and Electricity*, UCD-ITS-RR-97-5, Institute of Transportation Studies, University of California, Davis, February (1997). 150 pp.

M. A. Delucchi, *A Revised Model of Emissions of Greenhouse Gases from the Use of Transprtation Fuels and Electricity,* UCD-ITS-RR-97-22, Institute of Transportation Studies, University of California, Davis, November (1997). 210 pp.

Results are published in two articles in the peer reviewed literature:

M. A. DeLuchi, "Greenhouse-Gas Emissions from the Use of Transportation Fuels and Electricity," *Transportation Research-A* **27A**: 187-191 (1993).

M. A. Delucchi, "A Lifecycle Emissions Analysis: Urban Air Pollutants and Greenhouse-Gases from Petroleum, Natural Gas, LPG, and Other Fuels for Highway Vehicles, Forklifts, and Household Heating in The U. S.,"*World Resources Review* **13** (1): 25-51 (2001).